TIMING PERFORMANCE OF THE CMS ECAL AND PROSPECTS FOR THE FUTURE

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**TIME MEASUREMENT USING CMS ECAL**

- **Lead tungstate** has fast scintillation response
  - about 80% of the light emitted in 25 ns
- Shaping time (~40 ns) and sampling rate (40 MHz) allows for excellent time resolution
- Each pulse shape **made of 10 samples**
- Time extracted from **ratios of consecutive samples**
  - first three samples not used (pedestal determination)
- **Uncertainties** from noise fluctuations, pedestal subtraction, and 12 bit truncation
  - in time extraction correlations included
Precise Time Determination: Motivations

- Precise ECAL time determination crucial in many respects:
  1) energy determination require at least O(1 ns) resolution
  2) out of time background rejection
  3) beyond SM particle identification

- At test beam (TB) in 2008 intrinsic ECAL time precision measured to be better than 50 ps
  \[ \sigma(t) = \frac{N}{A_{eff}/\sigma_n} \otimes C \text{: N(oise) term 30 ns and C(onstant) term 20 ps} \]

- For collisions several effects worsen precision
  - run by run variations, inter-calibration, effects vs energy, radiation, B field, tracker material, ...

- Need to evaluate performance @ collisions
  - test beam results reproduced? calorimeter calibrated vs time?

- Understand limiting factors for O(10 ps) resolution crucial to design a possible ultrafast ECAL for HL-LHC future upgrade
**MEASURING TIME RESOLUTION: METHODS**

**From Z electrons (barrel EB)**
- Time of electron = highest crystal energy deposit of electron
- **Compare time of two electrons** after accounting for time of flight differences due to primary vtx position

**From photon-like ECAL deposits (barrel EB)**
- cluster shape requirements to look like a real em deposit
- no isolation requirements (π⁰ are fine) applied
- **Compare time of neighbouring crystals** of ECAL cluster with similar energy
- Similar to TB analysis (where electrons were used)
FEATURES AND LIMITATIONS

• PROs:
  – determining full detector performance (crystals far each other)

• CONs:
  – low statistics
  – shower development effects

• PROs:
  – good for determining intrinsic time measure performance
  – many systematics cancel out

• CONs:
  – not sensitive to effects dependent on geometry/segmentation/electronics (crystals close each other)
• **Resolution** from gaussian fit of core of $t_1-t_2$ distribution
• Results are for 2011+2012 data (only barrel shown)
• Resolution vs **effective amplitude**
  - $A_{\text{eff}} = A_1 A_2 / \sqrt{A_1^2 + A_2^2}$
  - $A_1$ and $A_2$ amplitudes of the two crystals normalized to noise (corresponding to ~40 MeV)
• **Noise term** consistent with TB
• **Constant term** about 150 ps
  - value ok for almost every physics application
  - but far from TB results
• **Next step**: understand what’s causing worsening
**Neighbouring Crystals: Results**

- **Noise term** consistent with TB
- **Constant term** about 70 ps!
  - much closer to test beam results
  - clear difference between Z and neighboring crystals results

![Graph showing comparison between test beam and collisions results.](image)
SAME AND DIFFERENT READOUT

- Resolution checked when **crystals belong to same or different readout (RO) unit** (25 crystals)
  - check if worsening in resolution correlated with electronics
- Results show quite **different constant term** (67 ps vs 130 ps)
  - effect not yet fully understood and under investigation

\[
\sigma(t) = \frac{N}{A_{\text{eff}}/\sigma_n} \pm \sqrt{2C}
\]

- **same readout**
  - \( N = 35.1 \pm 0.6 \text{ ns} \)
  - \( C = 0.0668 \pm 0.0003 \text{ ns} \)
- **different neighboring readout**
  - \( N = 34.3 \pm 0.7 \text{ ns} \)
  - \( C = 0.1295 \pm 0.0003 \text{ ns} \)
STABILITY VS TIME AND PSEUDORAPIDITY

- Performance verified vs time (run) and pseudorapidity
  - both could reveal effects due to luminosity and radiation
- **Stable in both cases** (variations within 10-20%)
  - crystal time response not yet affected by radiation
  - calibration robust vs time
@ HL-LHC average number of **multiple interactions up to 140**

**Issue for calorimetric quantities**
- many hits saved per event (issues in trigger, reconstruction)
- extra pile-up (PU) hits degrade resolution of high-level objects
  - $\gamma$, e, Jets, MET, isolation quantities

**Example: Jet Response**
- 30-40% of Jet energy due to neutral particles
- *more than 70 GeV extra energy* in average for 140 PU
- subtracted but jet resolution degraded

➡ **Exploit ECAL time measurement to remove extra PU energy deposits**
**Vertex Determination using Timing**

- **O(ps) timing detector**
  - simulated and integrated with present ECAL and CMS reconstruction to study PU mitigation

- Different time resolutions investigated

- **Vertex determination** in low track multiplicity events ($H \rightarrow \gamma \gamma$)

- Vertex position from *constraint that both photons* originate from *same vertex*

- **$O(30 \text{ ps})$ time resolution $\Rightarrow < 1 \text{ cm}$ precision in $z_{vtx}$ determination in forward region**
  - beam spot spread in $z_{vtx}$ is now $\sim 6 \text{ cm}$

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**CMS Simulation Preliminary**

$H \rightarrow \gamma \gamma$ events
both photons with $1.5 < |\eta(\gamma)| < 3$. 

![Graph showing vertex resolution vs. time resolution](image-url)
ECAL Clean-up Using Timing

- **Effect of timing cut** on $\sum E_T^{ECAL}$ variable
  - sum of all ECAL hits with $E > 1$ GeV.
- O(30 ps) resolution detector simulated
- Require ECAL timing (time-of-flight subtracted) within a 90 ps window
- Most of the **PU extra energy gone**
  - able to almost recover no PU conditions
- Timing-based selection looks promising for high PU environment
CONCLUSIONS

• ECAL timing performance @ p-p collisions determined using electrons and photons

• Precise time determination achievable with present CMS ECAL
  – 70 ps resolution constant term for neighbouring crystals
  – 150 ps resolution constant term on full ECAL detector
  – much better than design (O(ns) resolution)

• Results stable vs time and pseudorapidity
  – Some readout unit-dependent effect under investigation

• An ultra-precise timing ECAL detector (resolution better than 30 ps) can play important role for HL-LHC
  – ps effects in time distribution system to be carefully considered

• Pile-up rejection based on timing looks promising to reduce ECAL occupancy
  – more details in Adi Bornheim’s talk on Thursday
STABILITY VS TIME AND PSEUDORAPIDITY

- Performance verified vs time (run) and pseudorapidity
  - this is for crystals in different RO units
• Performance verified **vs RO unit**
  – this is for crystals in same RO unit
PILE-UP JET-ID USING TIMING

- **Pile-up jet removal** based on **precision ECAL timing** compared to track-based and shape-based algorithms presently used in CMS
- **O(10 ps)** timing detector is simulated with present ECAL geometry
- **Time corresponds to time of most energetic crystal of a jet**
- **Pile-up removal promising**

![CMS Simulation Preliminary](image1)

![CMS Simulation Preliminary](image2)